

# The Doppler Paradigm and the APEX-EPOS-ORANGE Quandary<sup>1</sup>

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## Abstract

The experimental detection of the sharp lines of the ( $e^+e^-$ ) Puzzle is viewed as a struggle against Doppler broadening. Gedanken experiments which are realistic in zeroth order of detail are analyzed to show that the ORANGE and EPOS/I geometries select narrower slices of a Doppler broadened line than spherically inclusive (APEX and EPOS/II –like) apparatus. Roughly speaking, the latter require event-by-event Doppler reconstruction simply to regain an even footing with the former. This suggests that APEX' or EPOS/II's coincident pair distributions must be statistically superior to those of EPOS/I or ORANGE in order to support a comparable inference about sharp structure. Under such circumstances, independent alternative data is invaluable. Therefore, a corroboration of Sakai's 330.1 keV ( $< 3$  keV wide) electron line in few MeV  $e^+$  or  $e^-$  bombardments of U and Th targets could prove crucial.

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## 1. Introduction: Defeating Doppler Broadening of Sharp ( $e^+e^-$ ) Pairs

The most recent APEX [1, 2] and EPOS/II [3] U+Ta experiments report no evidence of the sharp ( $e^+e^-$ ) pairs observed in earlier experiments of the EPOS/I [4, 5, 6] and of the ORANGE [6, 7, 8] collaborations. We here view all of the experimental searches for sharp pairs as incognizant attempts to detect a set of sharp lines which have been Doppler broadened into a smooth distribution. It is then possible to continue to believe *all* the data, including the null results, and even to see in them clarifications of old puzzles. This viewpoint also suggests the selective culling of pairs as a fully parallel alternative to the use of apparatus designed to defeat Doppler broadening.

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To explore this viewpoint, we utilize gedanken experiments which detect the sharp rest frame energy of a uniform fully isotropic pair distribution emitted from a moving source. These experiments are analyzed for three experimental geometries.

The simplest “Spherically Inclusive (SI)” geometry resembles the APEX and EPOS/II experiments; it measures an energy distribution which exhibits the maximum possible Doppler broadening of the assumed distribution. The second class of “Bi-Hemispheric (BH) Selectors” resembles the EPOS/I apparatus, and measures a distribution whose Doppler width is reduced by its built-in selection of small values of the total pair momentum,  $P'$ . The “Angular Selectors (AS)” of our third geometry resemble the double-ORANGE apparatus and select a narrower distribution by preferring pair momenta which are perpendicular to the source velocity. It is remarkable that, from the perspective of the Doppler Paradigm, the two apparati which have reported sharp pairs emerge as well designed Doppler narrowers.

Under the guidance of these gedanken results, one learns that the Spherically Inclusive (SI) apparati accept the broadest possible distribution, and therefore begin the race one lap behind the Bi-Hemispheric (BH) and Angular Selecting (AS) Doppler narrowers. By applying event-by-event Doppler reconstruction to its pairs, an (SI) machine which gathers complete pair information may largely overcome this handicap. However, at the present level of precision, such processing merely brings them up to rough parity with the selectors.

The question arises whether the bi-hemispheric data subset of the spherically inclusive machines, enhanced by event-by-event reconstruction, might provide the best prospect for improved data quality.

As a by-product of this viewpoint there emerge also new insights, such as the expectation that the ORANGE apparatus will detect underlying sharp lines whatever the source velocity, but at energies modified by an averaged Doppler shift of second order in the source velocity.

## 2. The Smoothing of Sharp Lines by Lorentz-Doppler Broadening

### 2.1 The Uniform Isotropic $\Delta' = 0$ Data Distribution

Consider a pristine ( $e^+e^-$ ) pair distribution which has, in the rest frame of its source (wherein quantities are primed), a sharp sum energy shared equally between the electron and positron, and a fully isotropic distribution of pair sum and difference momenta. For specificity, we take a source with velocity,  $\mathbf{v}_S = 0.1c = \beta_S c$  in the beam direction, which emits pairs of sharp total energy, ( $\Sigma' = E'_+ + E'_- = 3.48 mc^2$ , corresponding to a pair kinetic energy,  $K'_T = 758 \text{ keV}$ , ) and an average lab energy of  $K_T = 750 \text{ keV}$ . The isotropy implies also that

these pairs have opening angles distributed uniformly in the range,  $0 \leq \cos \theta'_{+-} \leq \pi$ . Then the quantity  $(\gamma \beta_S p')$  which occurs frequently has the value of  $\sim 70$  keV. Also, since  $\beta_S$  is small and all of our leptons are very relativistic, we take the lepton angles in the lab frame to be equal to those in the rest frame of the source.

## 2.2 Transformation to the Laboratory

Note that in this distribution every pair has in the source rest frame a sharp delta function energy and there is no “background”. But the Doppler-Lorentz transformation to the lab frame spreads these sharp energies and momenta into a Doppler broadened distribution. Then a pair whose total momentum is  $\mathbf{P}'$  is observed in the lab to have the energy,

$$\Sigma = \gamma \Sigma' + \gamma \beta_S P' \cos \theta'_D = \gamma \Sigma' + D', \quad (1)$$

where  $\theta'_D$  is the angle between the source velocity and the total pair momentum, and  $D'$  is the “Doppler Shift”. (We note that for pairs with opening angles nearly equal to  $180^\circ$ ,  $P'$  is small, and the Doppler broadening of the summed energy is not important[10, 22], even if the decay occurs in a Coulomb field with a finite positron/electron energy difference, such as EPOS [5] observed in  $U + Ta$ .)

## 2.3 Gedanken Experiment #1: Spherically Inclusive Apparatus

Consider an idealized “Spherically Inclusive” or “(SI)” apparatus, which accepts all the pairs, and in particular all values of  $\cos \theta'_D$ . This apparatus will record a distribution of energies for these pairs which has an average energy,  $\Sigma^{SI} = \gamma \Sigma'$ , (because  $\langle \cos \theta' \rangle = 0$ ) and a width (defined here as twice the rms deviation from the average),

$$\Gamma^{SI} = 2\gamma\beta_S \sqrt{\langle (P'^2)/3 \rangle} = 2\gamma\beta_S p' \sqrt{2/3}. \quad (2)$$

Here  $\langle (P'^2) \rangle$  denotes the average of  $P'^2$  over the specified uniform opening angle distribution, equal in this case to  $2p'^2$ , where  $p'$  is the magnitude of either lepton momentum, and  $\langle \cos^2 \theta'_D \rangle = 1/3$ .

(Note that for “Spherically Inclusive” apparati which accept equally all pairs of the idealized isotropic data set, the width,  $\Gamma^{SI}$ , is independent of the direction of the source velocity, and therefore independent of the distribution of such directions. This property does not extend to the symmetry breaking apparati discussed below for which the assumed direction of  $\beta_S$  along the beam direction is therefore a nontrivial practical simplification.)

For the present (750 keV) example, the value of this width is  $\Gamma^{SI} \sim 120$  keV. If similar considerations are applied to an 805 keV line, then these two lines together yield in the lab a smooth distribution in energy over the range from about 690 keV to about 865 keV. Thus, the Spherically Inclusive apparatus will evidence in its pair sum energy distribution no hint that the the rest frame energy distribution is composed of two sharp delta functions. The extension to several lines, including perhaps some not yet identified, is clear.

## ***2.4 SI Apparati Require Doppler Reconstruction***

If reasonable source velocities can Doppler broaden the sharp pair decay lines beyond recognition in the energy distribution of the spherically inclusive (SI) apparatus, how can such an apparatus verify the underlying sharp lines experimentally? The answer lies in supplementary measurements sufficient to define for each pair its own Doppler shift,  $D'$ , and the utilization of these values to carry out an event-by-event Doppler reconstruction of the rest frame distribution. In principal such complete information is now available in the APEX and EPOS/II results, subject to some uncertainties. Then by subtracting its own value of  $D'$  from the measured lab energy of each pair, the rest frame energy (times  $\gamma$ ) distribution could be reconstructed.

For the APEX and EPOS/II experiments IPC pairs from  $^{206}\text{Pb}$  have been “re-narrowed” in this way to widths of the order of 40 keV [2, 9]. This width is presumed to be set by inaccuracies in the measured quantities comprising  $D'$  which prevent the reconstruction from realizing the true value, zero. We take this 40 keV magnitude to indicate that such event-by-event reconstruction can presently reduce the Doppler broadening of a pair by a factor of about  $40/120 = 1/3$ .

## ***2.5 Selection of the Unshifted Subset as an Alternative to Doppler Reconstruction***

An alternative to the Doppler reconstruction is the selection of a subset of pairs of small Doppler shift. Equation (1) states that every pair for which the inequality,

$$D' = \gamma \beta_S P' \cos \theta'_D \leq S, \quad (3)$$

holds, will be measured in the lab to have an energy,  $\Sigma$ , which is within  $S$  of ( $\gamma$  times) the sharp rest frame energy,  $\gamma\Sigma'$ . Here  $S$  is a pre-assigned limit chosen large enough to provide a statistically potent subset. Then a culling process, which retains only the “ $S$ -unshifted” subset of pairs (with values of  $D' \leq S$ ), and which discards all other observed pairs, emerges as an

alternative to Doppler reconstruction. The retained subset then reflects the energy distribution in the source rest frame, and a study of the subset may determine whether decay pairs of sharp energy occur in the ion rest frame. The answer “Yes”, would be indicated by peaks in the number of “S-unshifted” pairs per unit sum energy interval at ( $\gamma$  times) the rest frame pair decay eigenenergies.

## ***2.6 Culling, or Mixed Culling/Reconstruction May Be Advantageous in the Presence of Large Backgrounds***

For the idealized no-background distribution of our gedanken experiments, the Doppler reconstruction would seem to promise a better description of the rest frame energies than the S-subset culling process. But in the actual experiments, the background is large, and the signal is small. Then the wholesale Doppler transformation of background pairs required in the Doppler reconstruction might involve subtle disadvantages, which the simpler process of culling could perhaps mitigate.

Indeed, a mixed culling-reconstruction processes, in which both the quality and the magnitude of the term  $D'$  are assessed in deciding whether to discard the pair or to retain it for Doppler reconstruction, might offer an optimal extraction of information in the presence of large backgrounds.

We note also that the ORANGE and EPOS/I-like selector apparati discussed below execute automatic selections and rejections of pairs by virtue of their very construction. It seems difficult to argue that this method of choosing a subset of pairs is intrinsically superior to the culling process described above, especially when the culling selections are guided by an intelligent physical question. The essential question in the end is whether or not one discovers a true physical property of the system.

## **3. Selecting Unbroadened Pairs by the Geometry of the Apparatus**

We next consider how an apparatus might be designed specifically to select Doppler unshifted pairs from the laboratory distribution. The basis for such a design is implicit in the “unshifted” pair selection procedure outlined above: One seeks a design which selectively accepts pairs with small values of the Doppler shift,  $D'$ , of eq. (3), in order to achieve a measurement which is informative of the rest frame pair energy distribution.

For a fixed value of the source velocity, small  $D'$  values could be achieved by selecting small values of  $\cos \theta'_D$  or small values of  $P'$ , or both. In fact, the culling procedure described in sec.

2.5 above selects small values of the product of the two, by minimizing the Doppler shift itself, pair by pair, and is therefore manifestly optimal among such selections.

### 3.1. *Bi-hemispheric Selector Prefers Pairs with Smaller $P'$ Values*

A bi-hemispheric selector requires that of each pair, one lepton is emitted into the Right (R) hemisphere and one into the Left (L), as in the EPOS/I apparatus. Apart from this requirement, the acceptance range of electrons and positrons is broad in EPOS/I. In our idealized bi-hemispheric selector, we assume it is perfect: every electron (positron) emitted into to the Right (Left) hemisphere is accepted.

Then how does such a selector prefer small Doppler shifts,  $D'$ ? Obviously it accepts 1/2 of the pairs with opening angles near  $180^\circ$ . (The other half yield leptons in the wrong hemisphere.) But it accepts almost none of the pairs with opening angle near  $0^\circ$ , since they almost always emit both leptons into the same hemisphere. Then because the total sharp pair total momentum of our idealized isotropic data set is given by

$$P' = p' \sqrt{2(1 + \cos \theta'_{+-})}, \quad (4)$$

to select  $\theta'_{+-} \sim 180^\circ$  is also to select values of  $P'$  nearly equal to zero. (For more realistic data sets with  $\Delta' \neq 0$ , the smallest  $P'$  values are still selected by the  $180^\circ$  preference, although they are not then equal to zero. See Ref. [10]).

For intermediate  $\theta'_{+-}$  angles, the fractional acceptance for a pair with total momentum,  $P'$ , with solenoidal (i.e., w.r.t  $\mathbf{B}$ -field) angles  $\theta$  and  $\phi$ , is given by the expression,

$$F(\theta_{+-}; \theta) = \text{ArcCos}[\cot(\theta_{+-}/2) \cot(\theta)] / (4\pi^2). \quad (5)$$

for  $\{(\pi/2 - \theta_{+-}/2) \leq \theta \leq (\pi/2 + \theta_{+-}/2)\}$  and for  $\{0 \leq \phi \leq 2\pi\}$ . It is zero for other values of  $\theta$ .

With this weighting, we can calculate the width,  $\Gamma^{BH}$  by carrying out the average of  $D'^2$  for all pairs accepted from our uniform isotropic distribution. Again, we neglect the differences between primed and unprimed angles in the first approximation. For each  $\theta_{+-}$  value, the factor  $\cos(\theta_D) = \sin^2(\theta) \sin^2(\phi)$  must be averaged with the weight  $F$  over the angles  $\theta$  and  $\phi$  of the solenoidal coordinate system. Then that result, multiplied by  $P'^2$  from (4) provides for each pair opening angle,  $\theta_{+-}$ , the squared deviation of the energy from its unshifted value. Finally, the integral of the squared deviation over the uniform distribution in  $\cos(\theta_{+-})$  of the uniform

isotropic data distribution yields the following preliminary numerical estimate of the overall width of the pair distribution accepted by the bi-hemispheric selector:

$$\Gamma^{BH} = 2\gamma \beta_S p' \sqrt{(2)(0.08)} \sim 0.5\Gamma^{SI}, \quad (6)$$

Therefore, the BH geometry narrows the Doppler line by about a factor of two, comparable to the factor of three given by Doppler reconstruction of the IPC line in  $^{206}\text{Pb}$ . (The average energy of the distribution accepted by the BH selector is given by the (SI) value,  $\gamma \Sigma'$ , because the BH average for  $\cos(\theta_D)$  again vanishes.)

### 3.2. Angular Selector Prefers Small $\cos(\theta'_D)$ Values

We call an apparatus an “Angular Selector” (AS) if it prefers small  $\cos \theta'_D$  values. It is therefore complementary to bi-hemispheric selector discussed above, which prefers small magnitudes of  $P'$ . This third gedanken geometry resembles the ORANGE apparatus, accepting electrons on forward axial (about the beam) cones and positrons on backward cones, which cones lie within some range of angles. To analyze this apparatus, we momentarily idealize it so that it accepts only leptons emerging at a specific angle,  $\theta_O$  with the beam (instead of the range of angles,  $\theta_O^{MIN} = 35^\circ$  to  $\theta_O^{MAX} = 70^\circ$ , which the actual ORANGE detector accepts) and we imagine it to be in the rest frame of the source instead of the lab frame. Then it would accept *only* pairs from the uniform isotropic data set in which the total pair momentum  $\mathbf{P}'$  is perpendicular to the beam axis:  $\cos \theta'_D \equiv 0$ . Thus, this slightly idealized ORANGE apparatus is a *perfect* perpendicular selector, and therefore, a perfect Doppler narrower.

The fact that ORANGE may actually accept an electron at  $35^\circ$  and a positron at  $70^\circ$ , and vice versa, and that it is fixed in the lab, implies that some range of small but non-zero values for  $\cos \theta_D$  and for  $\cos \theta'_D$  is actually accepted. If the accepted range is centered at  $\cos \theta_D = 0$ , the  $\cos \theta'_D$  will then have a small average value  $\sim \beta_S d'/P'$ , where the coefficient,  $d'$  is defined by the average of  $D'$  over the accepted distribution. Then our idealized isotropic data set would produce in this angular selector apparatus a distribution with the average energy,

$$\Sigma^{AS} = \gamma \Sigma' + \gamma d' (\beta_S)^2, \quad (7)$$

(which exhibits a small Doppler shift, of second order in  $\beta_S$ ,) and with a width due to the range of acceptance angles equal to

$$\Gamma^{AS} = \sqrt{2/3} \gamma \beta_S p (\cos \theta_{MAX} - \cos \theta_{MIN}), \quad (8)$$

This (AS) width is smaller than the width, (Eq.(2), accepted by the idealized spherically inclusive (SI) apparatus by the factor,

$$\Gamma^{AS}/\Gamma^{SI} = (\cos \theta_O^{MAX} - \cos \theta_O^{MIN})/2 \sim 0.25. \quad (9)$$

The Angular Selector therefore narrows the line by a factor of about 1/4 from that measured by the Spherically Inclusive apparatus. This factor is to be compared with the factor, 1/2, for the Hemispheric Selector. Recall also that when the data of the Spherically Inclusive selector includes the information required for Doppler reconstruction, that process narrows the width by a factor of 1/3.

We thus arrive at the conclusion that in this zeroth order of complexity, the Spherically Inclusive (APEX and EPOS/II -like) apparatus is more blinded by Doppler broadening than the (EPOS/I and ORANGE -like) selectors, and that it acquires a comparable sensitivity only after event-by-event the Doppler reconstruction of its data.

### ***3.3 New Insights Into the ORANGE-EPOS/I Results***

This view of the the ORANGE apparatus as a suppressor of Doppler broadening also enlightens our view of its measured results, and of their relationship to the EPOS/I data by showing us that

(a) the ORANGE peak average energies ought not (NOT!) to be the same as those of EPOS. Rather, they should differ by a small (second order in  $\beta_S$ ) averaged Doppler shift, whose magnitude reflects the distribution accepted by the apparatus. Therefore, the differences between sharp energies of reported by the EPOS/I and the ORANGE collaborations should be viewed not as measurement errors, but as beckoning experimental hints;

(b) the ORANGE apparatus, presented with a uniform isotropic pair distribution from a moving source, will record peaks corresponding to energy delta functions of the rest frame for any magnitude of the source velocity, and not just for sources at rest in the heavy ion center of mass frame.

(c) Furthermore, in principle, the ORANGE experiment, at the cost of diminishing the counting rate, could, by simply decreasing the angular range of its acceptance cones, reduce the measured widths of its lines to the lowest value allowed by the experimental conditions. Thus when, viewed as a gedanken anti-Doppler experiment, it has the remarkable property of full adjustability of the width-acceptance: any desired narrowing can be achieved.

It is very important that the inference (b) above seems to conflict with the repeatedly published assertions of the ORANGE group that their source is nearly at rest in the center



of mass frame and that it could not possibly be moving with the velocity of the emerging projectile-like ion [8, 11]. The present author has however not found in the literature any specific supporting argument or evidence for these assertions. It would be appropriate for the ORANGE group to publish the detailed reasons for these claims, so that a review of their validity could be carried out, and a definitive conclusion reached whether any empirical evidence truly restricts the velocity of the source of the sharp U+Ta ( $e^+e^-$ ) lines.

#### 4. Sakai's Alternative Sharp Lepton Evidence Needs Corroboration

Very sharp ( $\Gamma \leq 2.1 \text{ keV}$ ) 330.1 keV electrons have been reported repeatedly [12, 13, 14, 15] by Sakai, et al. to emerge from irradiations of U and Th with energetic  $\beta^+$ -decay positrons. Furthermore, a scenario in which these are the electron partners of ( $e^+e^-$ ) pairs emitted from the same source as provides the pairs of the heavy ion “( $e^+e^-$ )–Puzzle” has been suggested [16, 17]. To test this connection it is essential to understand these sharp leptons better. One major experimental gap is the absence of studies with sharp electron and/or positron beams to corroborate Sakai et al.’s  $\beta$ -decay positron studies.

If Sakai’s data are true, they augment the ( $e^+e^-$ )–Puzzle of the heavy ion processes by providing invaluable evidence from an entirely independent direction. Before the very recent null results of EPOS/II became known, it had been our intention to devote this paper to the important question of those sharp leptons, and to urge experimental efforts to check Sakai’s work.

Instead, we simply note here that our analysis of the Sakai data suggests [18] that experiments with beams of 2 to 4 MeV electrons or positrons should expect to measure the sharp 330.1 keV electron and/or positron of the pair with a cross section of  $10^2 \text{ mb}$ . In addition, the scenario recommends (but in this case without a good estimate of the cross section) a search for these same sharp electrons and positrons with positron beams in the 660 to 795 keV resonance absorption range impinging upon U and Th atoms.

#### 5. Relevance of the Composite Particle $Q_0$ Scenario

For several years the author has considered a composite particle creation/decay scenario to be the simplest framework capable of encompassing all the data of the heavy ion “( $e^+e^-$ )Puzzle” [10, 19, 20]. About the internal structure of the composite particle, the data so far says nothing, but Occam’s razor prefers a bound Quadronium ( $e^+e^+e^-e^-$ ) atom-without-a-nucleus, as the soundest present choice: not inadequately simple, but invoking no unnecessary new hypothesis. We therefore refer to the scenario as the “Composite Particle ( $Q_0?$ ) Scenario”.

The Composite Particle ( $Q_0$ ?) Scenario allows for spontaneous Landau-Zener creation of  $Q_0$  from the vacuum in strong enough heavy ion Coulomb fields [21]. It also provides a good semiquantitative description [22] of EPOS’ observed sum and difference widths as arising from Doppler and Coulomb broadening. Thus, the central assumption of the  $Q_0$ /EPOS phenomenology that Doppler spreading defines the observed sum widths, augmented by the recent ORANGE evidence [8] that these pairs frequently have small opening angles, leads directly to the main idea of this paper: that Doppler spreading is the curtain which obscures the sharp decay lines of the  $Q_0$  eigenstates. The scenario also allows for [23] exotic decays of  $Q_0$  bound in a supercomposite molecule with a nuclear ion, emitting  $(e^-e^+e^+)$ ,  $(e^+e^+)$ ,  $(e^+)$ , and one- $\gamma$ , which have not yet been observed. Of these the single  $e^+$  Sharp Annihilative Positron Emission (SAPosE) [24] presents an inverse creation process, Recoilless Resonant Positron Absorption (RRePosA) [16], which may have been observed in Sakai’s studies mentioned above.

Another of these  $Q_0$  bound supercomposite decays—the annihilation into one- $\gamma$ —may already be in evidence as the 1780 keV gamma ray commonly attributed to Uranium nucleus: if the IPC or EPC continue not to suffice, then the observed gamma may just be an alternative decay product of the bound  $Q_0$ .

The C( $Q_0$ ?) Scenario survives the claim [25] that all such composite particles are excluded by high precision Bhabha results. The argument is based upon assumptions, not measurements [26, 27, 28]. So far one can say that  $Q_0$ , if it exists, must be strange, and that it might offend our intuitions, but never that it contradicts known physics.

## 6. Summary and Conclusions

When the experimental efforts of the “( $e^+e^-$ ) Puzzle” are viewed as an incognizant struggle to detect the sharp lines underlying a smooth Doppler broadened distribution, then the ORANGE and EPOS/I apparati are recognized as excellent “Doppler Narrowers”, while the APEX and EPOS/II effect no narrowing at all. Gedanken experiments on an idealized uniform isotropic pair data set exhibit these differences.

In this zeroth order of complexity no very narrow lines are selected from the uniform isotropic distribution by any of the apparati, leaving the explanation for the sharp ORANGE-EPOS/I lines to be sought in more specific properties of the actual distributions and/or of the actual apparati. Also the inferiority of the APEX-EPOS/II geometry is brought to parity with the selectors, but not to clear superiority, by event-by-event Doppler reconstruction based on the detailed supplementary data for every pair. Thus the benchmarks of this Doppler

Paradigm suggest that data from the APEX-EPOS/II geometries must be substantially superior statistically to ORANGE-EPOS/I data merely to match their Doppler narrowing capacities.

This viewpoint suggests also that differences between the EPOS' and ORANGE's measured sharp energies must be expected, and that they should be attributed to a second-order Doppler shift which reflects the accepted distribution.

The Doppler Paradigm's proposed view of the  $(e^+e^-)$ -Puzzle problem hinges upon its assumption that the sharp U+Ta lines originate in a source moving with an emergent ion velocity. It therefore directly confronts the repeated assertions [8, 11] of the ORANGE group that this assumption is excluded by their data.

In an ambiguous situation such we now confront, independent alternative data can serve a crucial role. We note that Sakai, et al. have repeatedly reported measuring (very!) sharp electrons from bombardments of heavy atoms by beta decay positrons. We urge that those studies be checked by analogous experiments with beams of few MeV electrons or positrons.

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